SPINNING OF TESLA-TYPE CAVITIES: STATUS OF ART

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Abstract - The spinning process developed at INFN-LNL is an interesting alternative among all seamless technologies. The cavity is straightforwardly spun from a circular blank by a cold forming process and no intermediate annealing is required. The actual procedure for prototype spinning foresees a fabrication rate on the order of one resonator per day, but it can be increased to several times that rate. Tests at DESY and at Jefferson Laboratory (Jlab) on mono-cells have demonstrated that the TESLA specifications can be reliably achieved. Moreover, it has also been demonstrated that spinning perfectly combines with other technologies such as the sputtering of Niobium onto Copper developed at CERN, and the Niobium Clad Copper developed at KEK.

1. INTRODUCTION

Eventually, the problem of mass scale production of resonators for TESLA will be faced. It is rather improbable that the most convenient way to produce the necessary resonators will be by drawing, trimming, assembling and Electron Beam (EB) welding 180,000 half-cells.

Within the framework of the TESLA Collaboration, the LNL of INFN proposed an innovative technique for avoiding the EB welding of Niobium. Seamless cavities can be cold formed at a rate of almost one cell per hour, by spinning a simple circular blank onto a suitable mandrel. No matter the number of cells, no intermediate annealing is required. The mandrel is made collapsible to permit easy extraction from the cavity once the spinning process is finished. The extraction of the mandrel parts from the cavity generally takes a few minutes, depending on the complexity of the cavity shape. The presence of an internal mandrel permits very tight tolerances. As a consequence, the resonant frequency distribution of spun cells has a low standard deviation. Generally, the limiting parameter for all tube-bulging techniques, such as hydroforming or explosive forming, is the material elongation limit, because of fracture propagation that occurs as this limit is approached. For spinning, the material elongation limit is of minor importance because the material is plastically displaced along all three dimensions. Moreover for the spinning process, both texture degree and grain size of the parent material are much less critical than they are for hydroforming.

2. STATUS OF THE ART AT LNL

The spinning process for a Copper mono-cell cavity is displayed in Fig. 1.

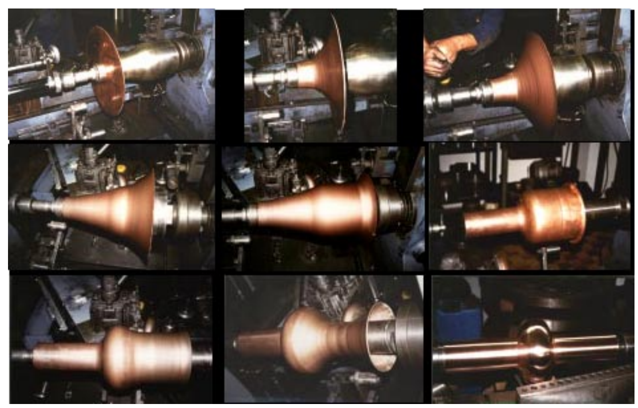


Fig. 1 - Spinning of a seamless, mono-cell resonator from a circular blank. No intermediate annealing is required during forming.

If the collapsible mandrel is suitably designed, medium beta cavities, such as the 0.4 beta cavity shown in Fig. 2, can easily be spun. However, for shorter gap cavities, a low melting point alloy mandrel becomes preferable to a collapsible one, since in this situation a collapsible mandrel becomes difficult to design and time-consuming to dismount. Even in such a case, the internal mandrel can be avoided by using an external template, or a numerical control machine. The penalty for this approach will be a higher internal surface roughness.

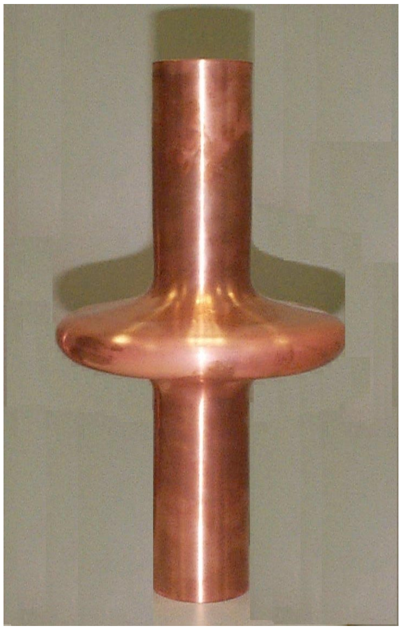


Fig. 2 - A beta 0.4 seamless resonator spun from a circular blank

If a larger blank is chosen, a multi-cell cavity can easily be spun. Also in this case no intermediate annealing is required. Fig. 3 refers to the spinning of an aluminum, 1.5 GHz, 10-cell resonator spun from a planar blank 3 mm thick and 1 meter in diameter. At the current state of technology we have successfully spun 9-cell copper and 5-cells niobium resonators. The limitation however, is not conceptual but is only in the tooling adopted.

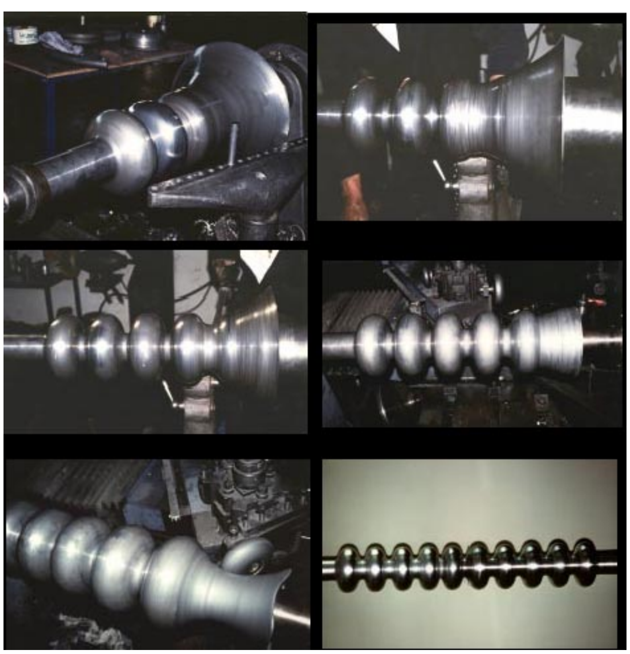


Fig. 3 - Spinning of a seamless, multi-cell resonator from a circular blank.

Spinning a multi-cell cavity from a disk is possible, but it is not practical for industrial production. In this case, the blank is initially spun into a conic frustum. The cells are subsequently spun from the frustum, which becomes lower and lower in height after each cell is spun (Fig. 3). The result of this operation is that the machine parameters (feeding speed, number of passes, shape of rollers, …) depend on the quantity of the remaining material, which is different for every spun cell.

This problem does not occur when spinning a multi-cell cavity from a tube, because the spinning procedure is the same for every cell. It should even be possible to spin simultaneously all the cells in one operation.

Niobium seamless tubes however, are not commercially available and the development of such tubes would be compulsory for the construction of 20,000 resonators.

In order to get seamless tubes suitable for the spinning process, we are simultaneously developing three different methods: forward flow-turning, and both direct and reverse deep-drawing.

Deep-drawing gives poorer tolerances when compared with flow-turning, but it is preferable for mass production because of the low costs and the reduced manufacturing time. For the deep drawing process, a circular blank is first drawn into a cup. It is then redrawn into smaller diameter parts as sketched in Fig. 4.

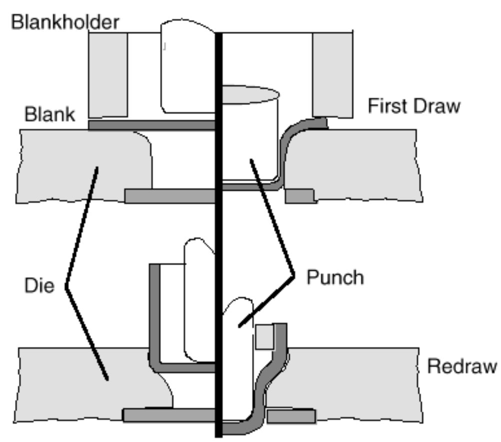


Fig. 4 – Direct Deep-Drawing of seamless tubes from circular blanks. Top picture: First drawing of a blank. Bottom picture: Redrawing of the cup into a taller one with a smaller diameter. On the left is displayed the configuration before drawing, while that on the right is during the operation.

Seamless Niobium tubes (208 mm in diameter and up to 700 mm in height) were successfully deep drawn from 3 mm disks of 800 mm diameter. In the case of direct deep-drawing, four steps were needed and again no intermediate annealing was required (Fig. 5).

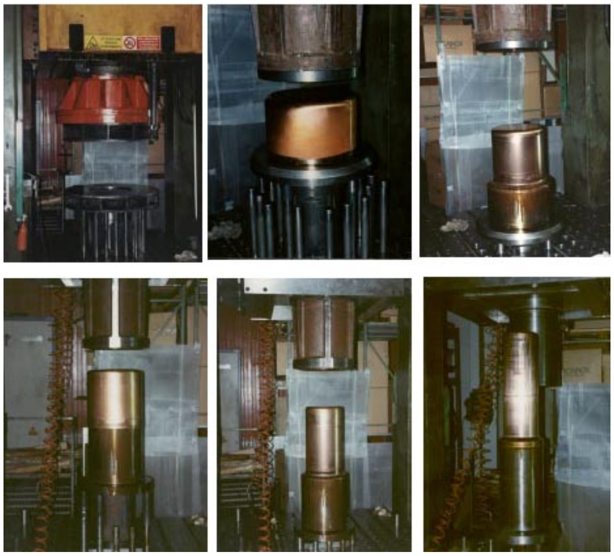


Fig. 5 - Direct Deep- Drawing of Seamless tubes from a circular blank. Tubes with heights of four times the diameter can easily be obtained without intermediate annealing.

In the author's experience, the only drawback expected in direct deep-drawing is the high roughness of the tube's internal surface. However, one can easily get rid of it by reworking the tube on a steel mandrel by flow-turning.

Reverse deep-drawing gives an internal surface with a sub-micrometric roughness. As seen in Fig. 6, the first operation in reverse deep-drawing is the same as in the direct deep-drawing process. The difference is in the redrawing steps: the punch pushes the tube from the bottom, with the difference that it is plugged externally to the tube rather than internally. Therefore, after each redrawing, what was the external surface of the tube becomes the internal surface, and vice versa.

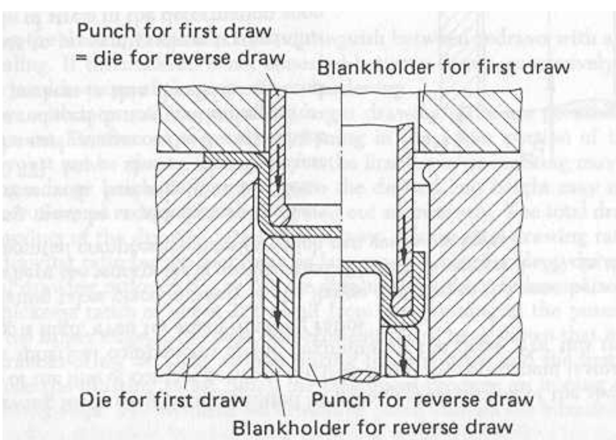


Fig. 6 - Reverse deep-drawing of seamless tubes. On the left it is displayed the configuration before drawing, while on the right is that during the operation.

The reverse deep-drawing operation is visible in Fig. 7. Niobium tubes have been drawn again without the need of intermediate annealing.

Fig. 7 – Reverse deep-drawing of seamless tubes. During each redrawing, the external surface of the cup to be drawn becomes the internal of the drawn part.

We have also produced seamless tubes by forward flow-turning. A circular blank of 8 mm thickness is preliminarily spun into a short thick tube, then ironed by three rollers onto a mild steel mandrel, as shown for the Copper part in Fig. 8. In just one pass, the pre-formed piece is transformed into a thinner and longer tube. With such a technique the material hardness is substantially higher in value than that obtained by deep-drawing. The thickness is uniform within a few hundredths of a millimeter; and the internal roughness is sub-micrometric, depending on the degree of finishing of the mandrel surface onto which the tube is flow-turned.

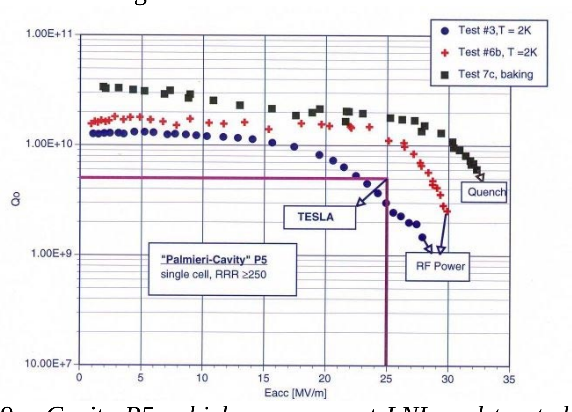
Fig. 8 – Forward flow-turning of seamless tubes. A short, thick tube is spun or drawn from a planar disk. Then the tube is thinned by three roller spinning.

The cost production of 20,000 tubes made by flow-turning is substantially higher than the cost of the same amount of tubes produced by deep-drawing. Wall thickness uniformity is more consistent with the former, but in a certain sense it is not required for spinning a cavity. The problem of which technique to adopt for mass production is a focal point, but it is still open and it cannot yet be addressed. Nevertheless in the author opinion for a large number of pieces, the most favorable technique could be an initial deep-drawing of a thick blank followed by a wall thickness reduction to the desired thickness by forward flow-turning. We have not investigated the backward extrusion of Niobium tubes from a Niobium billet. This technique, even while using expensive tooling, could actually result in cost savings, since the sheet-rolling steps are skipped.

3. RF MEASUREMENTS AND RESULTS

The approach followed in this research program on spun cavities tries to make use of international collaboration in the most fruitful form. The cavities spun at LNL have been sent to different groups abroad. LNL has been promoting for many years R&D programs on spinning. On the other hand it is well known that both Jlab and DESY have a recognized expertise in the search for high gradients; KEK has mastered the technology of Niobium electropolishing and that of Niobium clad Copper; and CERN that of Niobium sputtering onto Copper. Joining together in a collaboration the above mentioned specialist and their resources is evidently the most fruitful thing to do.

In this framework, the cavity of Fig. 9, a 1.5 GHz mono-cell, was treated and tested by P. Kneisel at Jlab. The cavity has undergone several treatments. However, only after a mechanical grinding of the internal surface plus *an in situ baking* at 115 C, did the cavity reaching a Q_0 of 5e+9 and a gradient of 33 MV/m.



4.

Fig. 9 – Cavity P5, which was spun at LNL and treated and tested at Jefferson Lab. Test 3 was performed after removing 230 microns with BCP. Test 6b was performed after 100 hrs of tumbling, 80 microns BCP, 90 minutes of heat treatment, 60 microns of BCP, a further grinding of cracks at the beam pipe and last 50 microns of BCP. Test 7c was performed after an additional 20 microns BCP followed by 40 hrs of baking in situ at 115 C.

The plot in Fig. 10 refers to a 1.3 GHz mono-cell cavity spun from a Niobium clad Copper disk, and measured at KEK by K. Saito. The accelerating field achieved is 25 MV/m at Q_o of 1e+10. Slow cooling is compulsorily in order to avoid thermoelectrically induced currents.

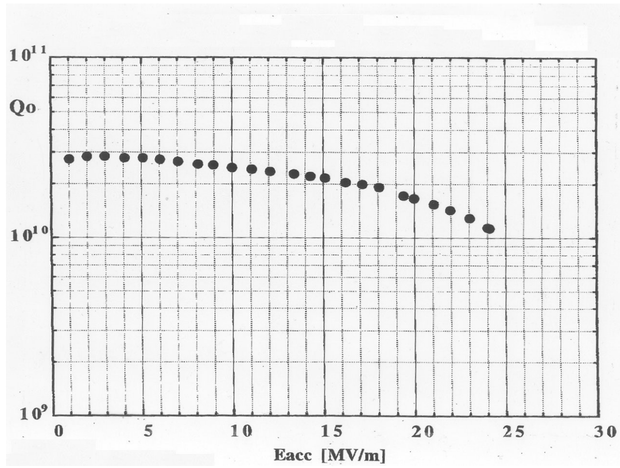


Fig.10 – The cavity Kenzo2, spun at LNL and treated and tested at KEK. The displayed measurement was performed after a removal of 90 microns by mechanical polishing, 2 hrs of annealing at 760 C, and a further 10 microns of electropolishing.

An interesting consideration could be deduced by such a result: Niobium clad Copper is a real alternative to bulk niobium. Moreover Fig. 11 shows that the main limitation of Nb clad Cu resonators is due to the cracks in Niobium after spinning. The fissures visible in the photograph are attributed to the different thermal expansions of Copper and Niobium. It is worthwhile to notice however, that they are located at the iris, the zone of the maximum material displacement. By a proper choice of the spinning parameters, the number of cracks can definitely be reduced.

Fig. 11 – Section of a Nb clad Cu cavity after vacuum annealing. Pre-existing cracks at the iris due to the material tensile strength at the time of spinning were amplified by the different thermal expansions of Copper and Niobium.

Micro-cracks on the internal surface are the main enemy to fight when spinning a cavity. Fig. 12 displays the cracks present on the internal surface of a Niobium resonator. The cracks, displayed longitudinally to the axis of the cavity, are an average of 30 microns deep (the magnification is such that the full photo width corresponds to 10 microns). The problem arising from the crack's presence is twofold: RF currents are obstructed, and the well of a crack is practically impossible to clean even by means of high pressure water rinsing. So A crack is a receptacle for contamination, BCP residuals, water, and so on.

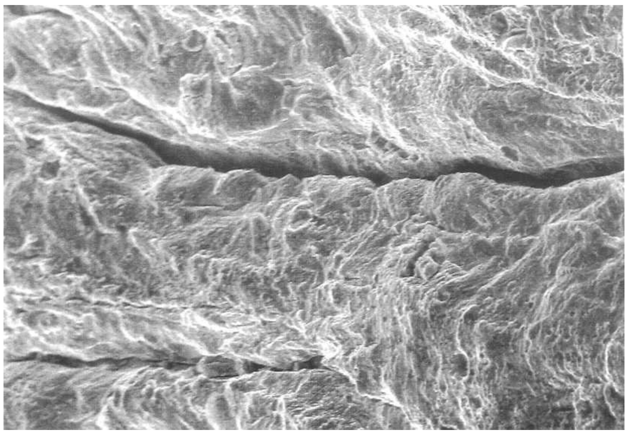


Fig. 12 – Typical longitudinal cracks present at the iris in spun cavities and due to the tensile elongation of Niobium.

Another confirmation of the impact of micro-cracks was given by cavity 1P3, a 1.3 GHz, mono-cell spun at LNL and measured at DESY first by M. Pekeler, then by L. Liljie. Several BCP treatments pushed the cavity a bit over 20 MV/m. Only 100 microns of mechanical grinding removed the cracks, which flattened the Q-value versus field, permitting a field of 30 MV/m to be achieved (Fig. 13).

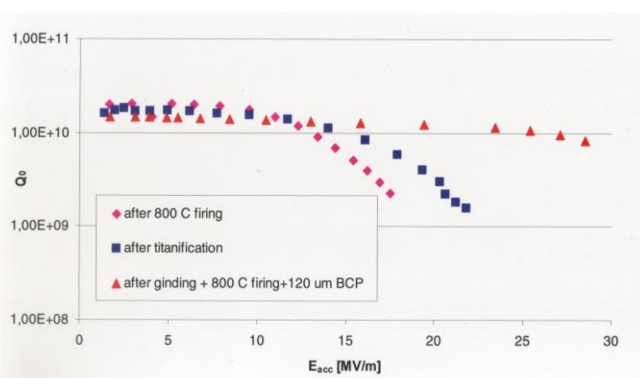


Fig. 13 – Cavity 1P3, spun at LNL, underwent several BCP treatments and the accelerating field never achieved 25 MV/m. After 100 microns of mechanical grinding, the Q-value versus field has become flat, reaching the field of 30 MV/m.

In this context it is very interesting to observe the behavior of the cavity P6 in Fig. 14. P6 was chemical etched by Kneisel at Jlab, then electropolished by K. Saito at KEK. The Q-factor is lowered, the curve becomes flat and the accelerating field limit is pushed forward.

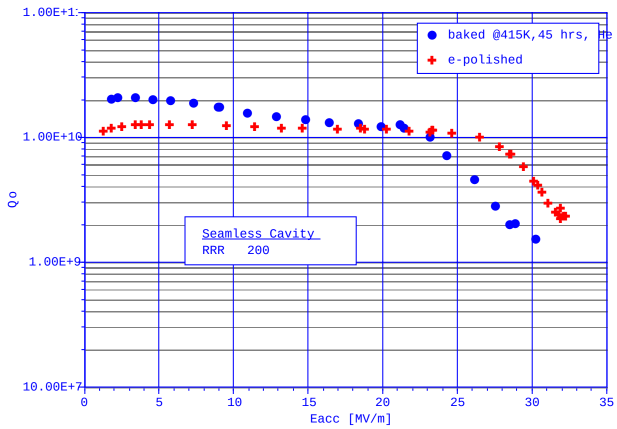


Fig. 14 – Cavity P6 was spun at LNL, processed at Jlab (BCP and thermal treatment), then electropolished at KEK.

Two five-cell and one four-cell resonators have been spun. Of the two five-cells, one has been treated and tested at Jlab, and the other has been treated and tested at DESY. The cavity tested at Jlab has achieved 12 MV/m in PI/2-mode and 25 MV/m in the PI/5-mode, showing the presence of defects in the end cell. On the basis of the experience with mono-cells, a further grinding of the cavity's internal surface is expected to be beneficial. As far as the five-cell cavity test at DESY is concerned, the accelerating field achieved at this time is 15 MV/m after 100 microns removal.

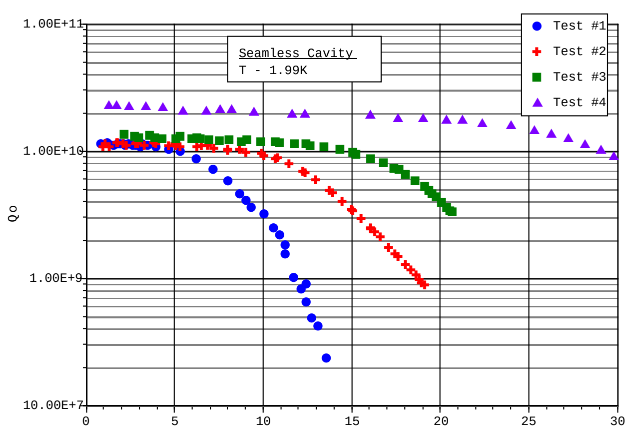


Fig. 15 - Cavity P7 was spun at LNL from a seamless tube formed by direct deep-drawing. The cavity was processed at Jlab and it achieved 30 MV/m after only 100 microns of BCP. Before spinning, the tube interior was mechanically abraded for around 30 microns.

Consistent with what is observed for mono-cells, the accelerating field values improve with greater material removal from the inner surface of the cavity.

Tube-spinning allows the forming of cavities with lower internal roughness. An example of this is seen with Cavity P7, which was spun at LNL from a direct deep-drawn tube. The cavity achieves 30 MV/m only after 100 microns of BCP.

It is also evident that a composite slab of thick copper sheet explosively cladded with a thin foil of Niobium presents several advantages: the cost saving due to the reduced amount of Niobium, but mainly the great advantage of high workability. The composite sheet behaves plastically as copper, while the thin layer of Niobium adapts itself to the copper. Spinning copper indeed is much more plastic and formable than any other material.

The Niobium sputtering onto a copper, 1.5 GHz cavity has been carried out by Benvenuti and Calatroni at CERN and the results are very promising: Q_0-factors over 1e+11 and accelerating field values over 20 MV/m.

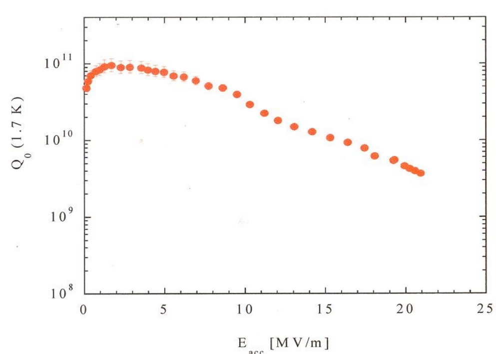


Fig. 16 – Cavity H8.2 has been Niobium sputtered at CERN onto a 1.5 GHz Copper spun substrate

In this framework, if 2000 cavities would be fabricated by sputtering a Niobium film onto Copper, the spinning of seamless Copper 9-cell resonators would be an easy problem to solve.

4. CONCLUSIONS

Seamless cavities represent a real possibility for mass scale fabrication of low cost resonators. Spinning resonators from seamless tubes is a technology that is easily transferable to industry. Preliminary results on mono-cells show that TESLA specifications can be met and exceeded.

5. ACKNOWLEDGMENTS

The Author has showed results obtained at Jlab, DESY, KEK, CERN on Cavities spun at the LNL of INFN. In this context, the experience of P. Kneisel, L. Liljie, D. Reschke, A. Matheisen, K. Saito, T. Fujino, and S. Calatroni is priceless. The author is also indebted toward D. Proch, D. Trines, P. Schmueser, C. Benvenuti, H. Wenninger for help and discussions.